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THE SPREAD OF OIL IN THE ARCTIC

by
DAVID P. HOULT
Massachusetts Institute of Technology
Cambridge, Massachusetts

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-- NOTES --

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David P. Hoult
Associate Professor
Massachusetts Institute of Technology
Cambridge, Massachusetts

Abstract

The problem of oil spreading over Arctic ice is studied. The main topics considered are, first, what is the rate of spread of oil released from a point on the surface? Second, how large does the area of the oil slick become before it is caught in the pockets of the ice surface? The random character of the ice surface controls the final size of the oil slick and its rate of spread. The theory of the spreading speed essentially balances a drag force against a gravitational driving force. The spreading theory contains one emperically determined constant. The experiments were performed in a small tank in the Fluid Mechanics Laboratory at Massachusetts Institute of Technology, using random surfaces constructed from plywood, gravel, and epoxy. The spread and final size of the spill, as observed, are in agreement with the predictions of the theory[4]. In addition, the results were compared with larger spills made in the high Arctic during two expeditions carried out by the U.S. Coast Guard[5],[6]. It is found that,properly scaled, the field data are in good agreement with both the laboratory data and the theory. These results serve to provide an understanding of the potential for oil pollution when oil is spilled in the high Arctic on either tundra or pack ice with no leads. A qualitative argument is given to show when the results can be applied to a surface of modest slope.

I. Introduction

In 1968, oil was discovered on the North Slope of Alaska. Since the world supplies of oil are dwindling and the prices rising, this oil must be used if the present standard of living is to be maintained at a reasonable cost. This means that the crude oil must be shipped to a place where it can be refined, and whether supertanker or pipeline is used, the oil will have to travel over the rough surfaces of the Arctic. A small fraction of all oil shipped is spilled. In order to deal with this environmental problem it appears necessary to gain an understanding of how oil spreads on or under ice. This understanding must come in two parts: first, the process of spreading must be understood and the time for spreading determined; and second, the final size of the oil pool must be determined.

In developing the spreading law, proper account must be taken of the characteristics of the rough surface. In order to solve the second problem, one must take into account the characteristics of the ice surface, namely its roughness and the random nature of this roughness. If this is done, the answer to the problem will be determined in a statistical way. This problem was studied by Patureau[7]. The purpose of this paper is to correlate results of experiments on a laboratory scale model and comparing these results with field data.

The experimental apparatus and procedure will be discussed in Section II. Since the results of Patureau are expressed in terms of parameters derived from the power spectrum of the surface, this section also describes the apparatus and procedure used to determine the power spectrum of the experimental surface. In Section III, the details of Patureau's final size theory and the spreading theory derived from the experimental results will be discussed, along with the assumptions and limitations. Section IV will present the results in the form of correlations between theory and experiment, an explanation of the derivation of the spreading theory, sources of error, and the conclusions of the study.

II. Experiments

In planning the experiments, the characteristics of Arctic ice were first studied. Earlier work had indicated that it was desirable to construct an apparatus that could dump a known volume of 'oil' at a fast rate[3]. This turned out later to not be the case.

To obtain dynamic and geometric similarity, certain scaling parameters must have suitable values. These are:

$$Re = \frac{(\Delta g\langle \bar{h} \rangle)^{1/2} \langle \bar{h} \rangle}{\nu} > 500$$

$$\beta = \frac{\langle \bar{h} \rangle}{T} \approx \begin{cases} 1/80 \text{ above} \\ 1/20 \text{ below ice} \end{cases}$$

N = number of pockets >> 1

A = density ratio <.2 (under only)

With the exception of Re, the conditions are all well met. In the case of the Reynolds number, a desire to use fluids that could be used easily, would not destroy plexiglass and would provide agreement with the other parameters led to a relaxation of the restriction. Water for the over ice experiments provides an Re of a little more than 400 and kerosene for the under ice case provides an Re of about 100. This is believed to provide sufficient turbulence to satisfy the theory.

A schematic of the spreading experiment apparatus is shown in Fig. (1). This figure should be referred to if any questions arise.

The rough surface itself was built by epoxying various sizes of rocks to a plywood board in a random fashion. The surface was then painted white with black concentric circles. When used in conjunction with a dyed fluid, the spread is easily observed and photographed. The size of the surface, and therefore the size of the tank,is 4' x 4'. This size tank offers a large enough surface to be

statistically significant and yet small enough to be easily handled.

In order to scale the laboratory model to a real spill, one should consider that the Arctic roughness height is on the order of 1' . The roughness height of the experimental surface is about 1/10 inch. This means that the 4' x 4' surface corresponds to about 500' x 500' in the Arctic.

Tha tank is made of plexiglass to allow the spread to be easily observed and photographed. The frame was designed to allow for rotation of the tank when conducting under ice experiments. This was necessary because if the tank were filled in a horizontal position the pockets in the surface would trap air and make the experimental results meaningless.

To record the progress of each experiment a Bolex 16mm camera with a 10mm lens and a variable time base was used. Since this lens needs a focal length of around nine feet to get a large enough field to cover the apparatus, it was decided to use a mirror. The camera was then run at a known speed, usually 20 fps, to record time. The developed film was then examined frame by frame to determine radius versus time and the final size.

To measure the surface a frame was made (see Fig. 2) and the elevation of the surface was measured. The variance and the power spectrum were then calculated by a computer program.

To test the isotropy assumption, traces were taken in perpendicular directions and then their power spectra compared. This is explained in Section IV.

The frame affects the spectrum only in the wavelength range greater than ten inches. The imperfections in the frame has no effect on the results.

For the over ice experiments, the fluid used was water dyed with food coloring. Soap was added to reduce the surface tension and the 'oil' was placed in the cannister. The apparatus was then leveled very carefully to prevent the fluid from running off to one side. Problems were encountered in this area. Once the experiment was ready to start, the camera was started and the stopper pulled. This released the oil at a fairly fast rate. In order to determine the amount released, the fluid level in the cannister was measured before and after the release.

The underwater experiments were considerably more difficult. The experiment had to be set up in such a way that no air pockets remained in the tank and no kerosene escaped through the feed lines connecting the tank to the cannister. To do this, water was first placed in the cannister to a level that would prevent the kerosene from getting into the feed lines. Then, enough kerosene, which was dyed using enamel paint, is added to fill the cannister. The rough surface was then placed on the tank and the tank was almost completely filled and then tilted to allow the air to escape from the pockets. The filling of the tank was completed in this position. When all the air escaped out the top and the tank was full, it was rotated back to a horizontal position and leveled. Since there was sufficient pressure in the tank to cause the surface to deflect at the center, water was bled off in an attempt to ensure that the surface was flat. Some degree of error was probably caused by this deflection. Once the tank was leveled and the pressures equalized, the experiments proceeded in the same way as the over ice experiments.

To check for the presence of viscous effects, experiments were run with glycerin-water and kerosene-oil mixtures. These experiments are described in the Appendix.

III. Theory

The theory that governs the spreading was developed as a result of data from the experiments described in the last section and the available field data.

In determining what will happen to oil spilled in the Arctic, two cases must be considered. In the case of a pipeline breakage, the oil will spread over ice and tundra. In the case of a supertanker accident, the oil may spread under the ice. This happens because Arctic ice has a specific gravity of about .8 and North Slope crude has a specific gravity of about .9 . Therefore, at an ice-water interface the oil will, on hydrostatic considerations, tend to spread under the ice. The spreading in both cases follows the same theory and the results differ only by a factor determined by the density ratio of water and oil.

Patureau's theory states that pockets in the ice are filled to the roughness height, $\langle \bar{h} \rangle$, and it was shown experimentally[9] that the value of the viscosity is not important. This means that as pockets in the ice are filled additional fluid flows over the filled pockets frictionlessly and the drag can act only at the edge over an area proportional to the radius multiplied by the roughness height. When attempting to correlate the laboratory data for over and under ice and the field data, it was found that the data would not scale with the volume released. It was found that[9] the rate of spread for a given surface could instead be correlated with using the rate of oil release, Q . Since the size of the final pool depends upon various statistical parameters, one can see that for a given volume and surface there will be an average pool size and an associated variance. In order to determine the accuracy of the averages, Patureau[7] developed an expression relating the standard deviation of the size with the average size.

Fig. 3 shows a sketch of oil being released on a rough surface with a roughness height $\langle \bar{h} \rangle$. The driving force is gravity, which causes a pressure at the outside edge of the spill. Thus,

$$F_g \sim \rho A \sim (\rho \Delta g h) h r \tag{1}$$

Since

$$h^2 \sim \frac{(Qt)^2}{r^4} , \tag{2}$$

the gravitational force from Eq. (1) can be expressed as

$$F_g \sim \rho \Delta g \frac{(Qt)^2}{r^3} \quad . \tag{3}$$

The pressure drop caused at the outer edge as the oil flows will be

$$d_p \sim C_f \, \rho U^2 \tag{4}$$

where C_f is a friction coefficient of order one. The area over which the drag acts if the roughness height, $\langle h^- \rangle$, times r . The retarding force becomes

$$F_r \sim \rho U^2 r \langle h^- \rangle \tag{5}$$

Replacing U in Eq. (5) with r/t and setting Eq. (5) equal to Eq. (3) gives

$$\rho \Delta g \frac{(Qt^2)}{r^3} \sim \rho \frac{r^3}{t^2} \langle h^- \rangle \tag{6}$$

This result can be written as

$$r \sim \left(\frac{\Delta g Q^2}{\langle h^- \rangle} \right)^{1/6} t^{2/3} \tag{7}$$

Eq. (7) can be non-dimensionalized by defining a scaling length

$$r^* = \langle h^- \rangle \tag{8a}$$

and a scaling time

$$t^* = \left(\frac{\langle h^- \rangle^7}{gQ^2} \right)^{1/4} \tag{8b}$$

To obtain an expression for the final size and the associated standard deviation several assumptions must be made[7]. The first of these assumptions equates the average of a sample from the surface with the ensemble average over the whole surface. It is assumed that the elevation of points on the surface are normally distributed about some mean. This assumption is in only fair agreement with the experimental surface, which actually is closer to a lag-normal distribution (and good agreement with the real ice surface)[7]. Under this assumption, the roughness height, $\langle h^- \rangle$, and the variance of the height, σ_h , can be related by the simple equation:

$$\langle h^- \rangle = \left(\frac{\sigma_h}{2\pi} \right)^{1/2} \tag{9}$$

Thirdly, it is assumed that pockets in the ice surface are filled to the mean roughness height(see Fig. 4). This greatly simplifies the theory, but is only a crude approximation. The accuracy of this assumption can only be determined by experiment. The fourth main assumption is that the number of pockets filled is always large enough to give a statistically meaningful result. This assumption is realistic. For simplicity the pockets have a rectangular shape[7] (square in the case of an isotropic surface). This was done strictly for computational reasons. For the purpose of this paper the surface will be assumed isotropic and the spill will be circular. The isotropy assumption will be shown to be a good assumption by comparing the power spectra along perpendicular paths of the experimental surface. Lastly, it was assumed that a two-dimensional power spectrum could be formed as the product of two-dimensional spectra. This assumption has no mathematical justification, but even if it were poor, no real error in the results would appear.

The final results of the theory are expressed in terms of parameters which are derived from the statistics of the sea ice surface. The first of these is the variance of the roughness, σ_h . Next are two parameters k and T derived from the power spectrum of the surface. For a one-dimensional spectrum, T is the wavelength of the peak of the spectrum and k is determined from the following equation:

$$P(\tfrac{1}{T}) = \frac{2\pi\sigma_h}{k^{1/2}} \exp(\frac{-2\pi}{Tk^{1/2}}) \cosh(\frac{2\pi}{Tk^{1/2}}) \tag{10}$$

To simulate sea ice, the product kT^2 should be greater than 50, or, in the two-dimensional case $(kT^2)^2$ should be greater than 2500. From $(kT^2)^2$, an additional parameter, Θ , can be determined from Fig. 6.

Following the assumption that the oil fills the pockets to the roughness height on the average, we get the equation

$$\langle V \rangle = \langle S_{max} \rangle \langle h^- \rangle \tag{11}$$

or, for a normal distribution,

$$\langle V \rangle = \langle S_{max} \rangle \left(\frac{\sigma_h}{2\pi} \right)^{1/2} \tag{12}$$

from Eq. (8).

To non-dimensionalize the results, Patureau introduced the concept of the 'most probable pocket' size,[7], that is, the most common size for a pocket on the ice. Defining the surface area of a most probable pocket as

$$S_{mp} = T^2 \; , \tag{13}$$

and the volume of a most probable pocket as

$$V_{mp} = \frac{T^2 \; 2(2\sigma_h)^{1/2}}{\pi^2} \tag{14}$$

we find the following dimensionless equation from Eq. (12):

$$\frac{\langle S_{max} \rangle}{S_{mp}} = \left(\frac{4}{\pi^{3/2}} \right) \frac{V}{V_{mp}} \tag{15}$$

To provide a measure of the accuracy of the above equation, an expression for the variance of the surface area, σ_s , was derived. This

expression is obtained by considering the pockets in the ice to be filled sequentially and independently. For ease of understanding, the derivation will be for the one-dimensional case. This can then be easily extended to the two-dimensional case.

Since the pockets each have a volume variance, $\sigma_{V_{mp}}$, and a length variance $\sigma_{X_{mp}}$ and since they are filled independently, the total variance σ_V will be expressed as the sum of the variance of the pockets filled:

$$\sigma_V = N\sigma_{V_{mp}} \tag{16}$$

The total length of the average one-dimensional spill, $<X_{max}>$ is equal to the length of a mean pocket, X_{mp}, multiplied by the number of pockets filled,N.

$$<X_{max}> NX_{mp} \tag{17}$$

$$\sigma_V = \left(\frac{V_{mp}}{X_{mp}}\right)^2 \sigma_x \tag{18}$$

Using Eq. (16)

$$\sigma_x = \left(\frac{X_{mp}}{V_{mp}}\right)^2 N\sigma_{V_{mp}} \tag{19}$$

or

$$\sigma_x^{1/2} = \left(\frac{X_{mp}}{V_{mp}}\right) N^{1/2} \sigma_{V_{mp}}^{1/2} \tag{19a}$$

In dimensionless form, this becomes, using Eq. (16):

$$\frac{\sigma_x^{1/2}}{X_{mp}} = \left(\frac{<X_{max}>}{X_{mp}}\right)^{1/2} \cdot \left(\frac{\sigma_{V_{mp}}}{V_{mp}}\right)^{1/2} \tag{20}$$

In the two-dimensional case, one finds

$$\frac{\sigma_s^{1/2}}{S_{mp}} \alpha \left(\frac{<S_{max}>}{S_{mp}}\right)^{1/2} \tag{21}$$

Where the proportionality constant can be defined as

$$\Theta = \left(\frac{\sigma_{V_{mp}}}{V_{mp}}\right)^{1/2} \tag{22}$$

with Θ as shown in Fig. 5. It is seen that Θ depends only upon the product kT^2. This yields

$$\frac{\sigma_s^{1/2}}{S_{mp}} = \Theta \left(\frac{<S_{max}>}{S_{mp}}\right)^{1/2} \tag{23}$$

which is the result presented by Patureau.

IV. Results

Figs. 6 and 7 show the power spectra for the surfaces 1 and 2, used in the experiments. The isotropy assumption can be checked by comparing the spectral points determined from paths taken perpendicularly. The two directions are distinguished by the use of open and closed symbols. By noting that there is little difference between the two directions, one can see that the isotropy assumption is a good one. Also shown on these figures are σ_h, k, T and Θ.

Figs. 8 and 9 show that the data for the final pool size for surfaces 1 and 2 respectively is in good agreement with Patureau's theory. The values of the scaling area and scaling volume are shown on the figures, where S_{mp} and V_{mp} are as calculated in Eqs. (13) and (14). The solid lines on the graphs are the average values of the final size from Eq. (15). The dashed lines on either side represent one standard deviation on each side of the average and were determined from Eq. (23). On these graphs, the open symbols represent over ice runs and the filled symbols indicate under ice runs. It appears that the under ice pools are slightly smaller. This effect is within experimental error.

Fig. 10 shows the dimensionless radius versus dimensionless time for both over and under ice cases using the results of Section III. Also shown on this graph is field data from Glaeser and Vance[3] and McMinn[6]. The equation that best describes the line in Fig. 11 is:

$$r = .25(\Delta g Q^2/<\bar{h}>)^{1/6} t^{2/3} .$$

The under ice data shown in Fig. 13 is plotted after allowing for a starting time. It was found that in the under ice case there was a significant lag between the time the stopper was pulled and the actual beginning of the spread. This was due to the time for the kerosene to float up through the water to the surface. This starting time was found to be about 1.5 seconds.

For the field data, the roughness heights are not known. Thus, the field data was fit to the solid line in Fig. 13 by adjusting the value of the roughness height. In most cases, the value of roughness height appears consistent with visual observations made in the field.

To expand the results of the laboratory experiments, one must know the characteristics, particularly the roughness height, of the Arctic ice. From laser profilometer traces taken in areas of high spill potential it has been determined that the roughness height varies greatly but is seldom less than three centimeters or greater than 60 centimeters. The size of a spill would be on the order of 10^4 cubic meters. Fig. 14 shows how the final radius of a spill varies with the roughness height and the total volume released. For an average volume and roughness height the final radius will be on the order of 300 meters.

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Fig. 11 Average Areal Coverage vs. Volume Released for a Spill on Arctic Ice

LIST OF SYMBOLS

$\langle \bar{h} \rangle$	roughness height of a surface
k	parameter describing rough surface that is determined from power spectrum
N	number of pockets filled
Q	rate of oil release
$\langle S_{max} \rangle$	average value of the surface area of a spill
S_{mp}	surface area of a mean pocket
T	wavelength of peak power spectrum
V	total volume of oil released
V_{mp}	volume of a mean pocket
$\langle X_{max} \rangle$	average value of the length of a spill (one-dimensional case)
X_{mp}	length of a mean pocket (one-dimensional case)
Z_o	roughness height of a surface
Δ	density ratio of water and oil, $\frac{\rho_\omega - \rho_o}{\rho_\omega}$
ρ_o	density of oil
ρ_ω	density of water
σ_h	variance of the roughness of a surface
σ_s	variance of the surface area for a spill
σ_V	variance of the volume for a spill
$\sigma_{V_{mp}}$	variance of the volume of a mean pocket
σ_x	variance of the length of a spill (one-dimensional case)
Θ	non-dimensional parameter which is the slope of the $\sigma_s^{1/2}$ vs. $\langle S_{max} \rangle$ relation

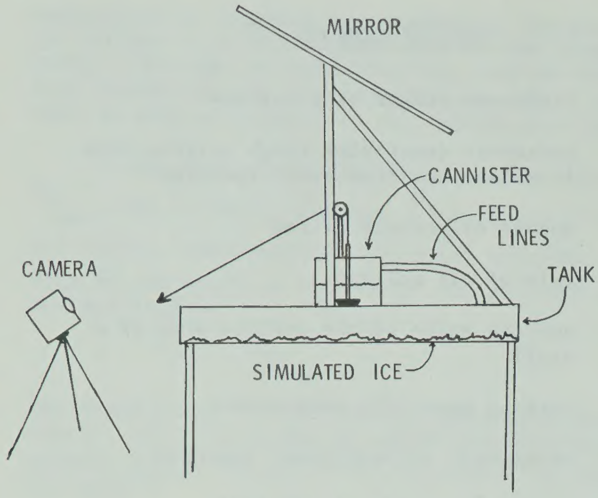

FIG. 1 SCHEMATIC OF SPREADING APPARATUS (OVER ICE SPREAD)

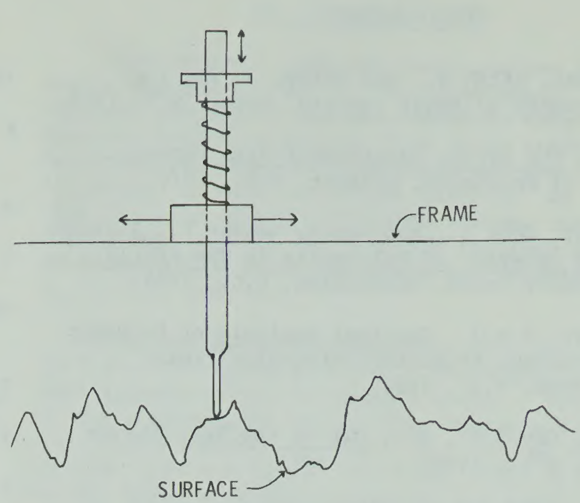

FIG. 2 SCHEMATIC OF APPARATUS TO MEASURE SURFACE

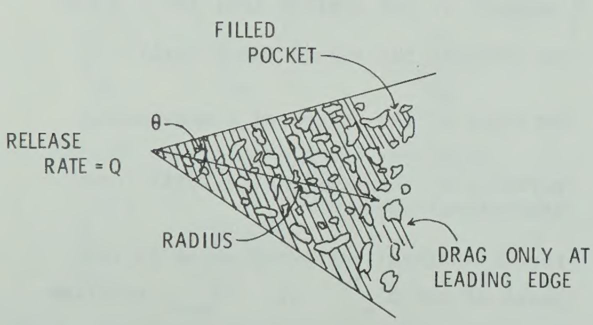

FIG. 3 SECTION OF OIL SPREADING ACROSS A ROUGH SURFACE

(ONLY θ OUT OF 2π SHOWN FOR EASE)

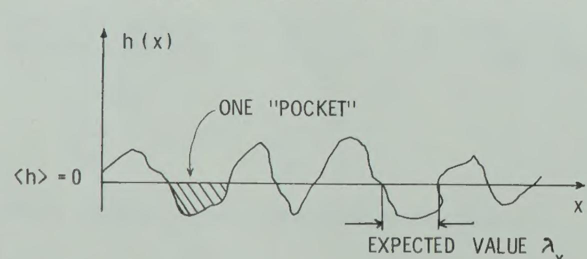

FIG. 4 AVERAGE LONGITUDINAL DIMENSION OF A POCKET

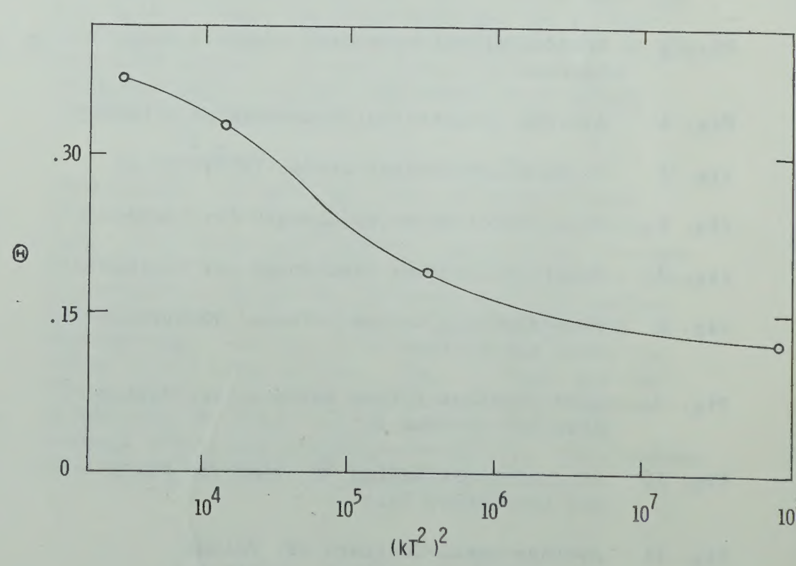

FIG. 5 Θ VS DIMENSIONLESS GROUP $(kT^2)^2$

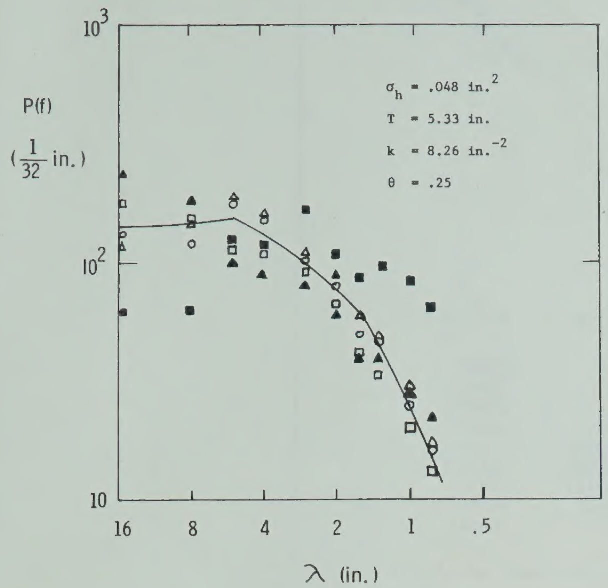

FIG. 6 POWER SPECTRUM vs WAVELENGTH FOR SURFACE 1

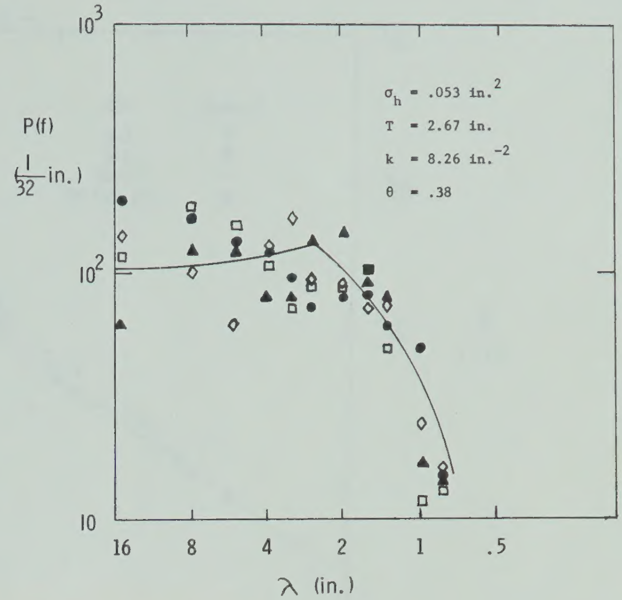

FIG. 7 POWER SPECTRUM vs WAVELENGTH FOR SURFACE 2

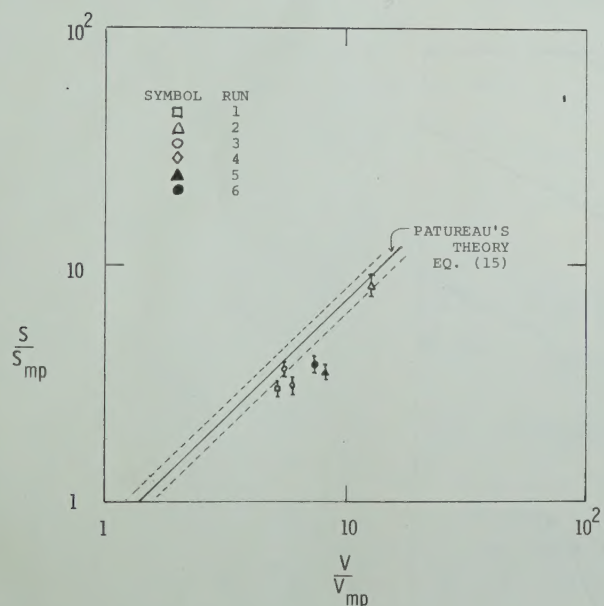

FIG. 8 DIMENSIONLESS VOLUME RELEASED vs SURFACE AREA FOR SURFACE 1

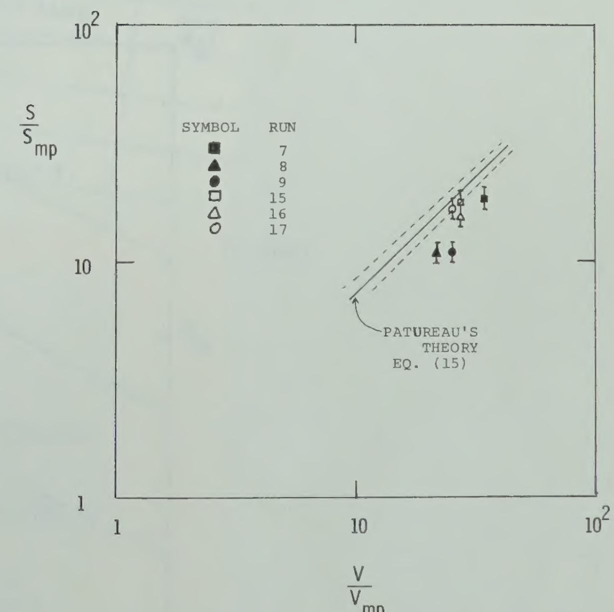

FIG. 9 DIMENSIONLESS VOLUME RELEASED vs SURFACE AREA FOR SURFACE 2

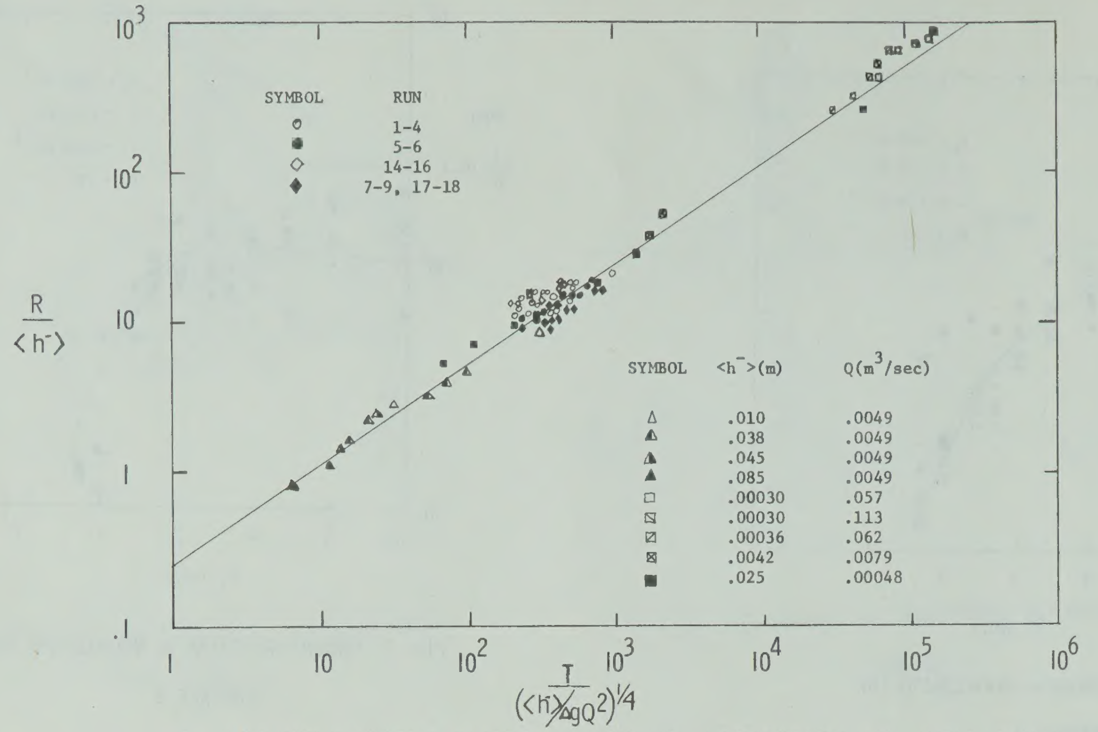

FIG. 10 DIMENSIONLESS RADIUS vs TIME FOR LABORATORY AND FIELD DATA

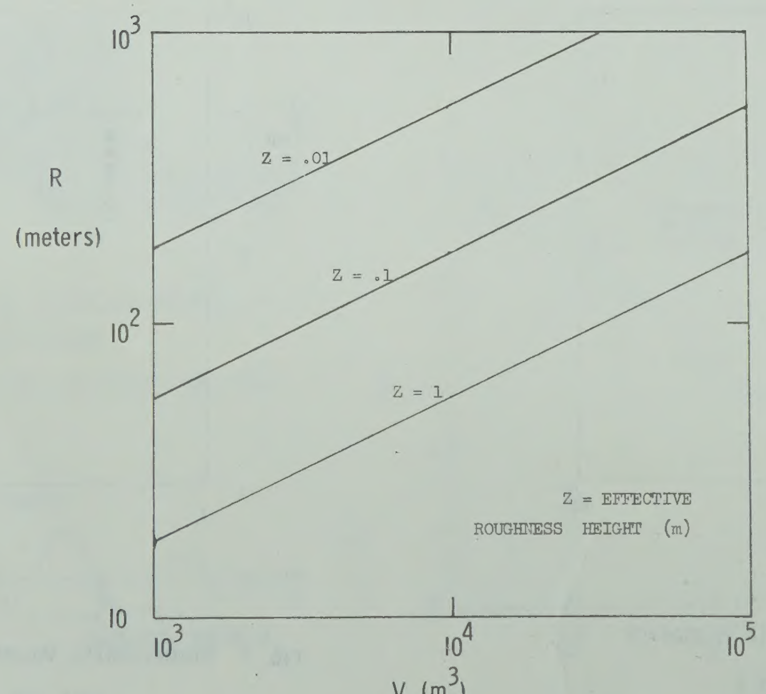

FIG. 11 AVERAGL AREAL COVERAGE vs VOLUME RELEASED

FOR A SPILL ON ARCTIC ICE

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